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VIRTUAL OBSERVATORY FOR ASTRONOMERS: WHERE ARE WE NOW?

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ABSTRACT

After several years of intensive technological development Virtual Observatory resources have reached a level of maturity sufficient for their routine scientific exploitation. The Virtual Observatory is starting to be used by astronomers in a transparent way. In this article I will review several research projects making use of the VO at different levels of importance. I will present two projects going further than data mining: (1) studies of environmental effects on galaxy evolution, where VO resources and services are used in connection with dedicated observations using a large telescope and numerical simulations, and (2) a study of optical and near-infrared colours of nearby galaxies complemented by the spectroscopic data.

Key words: Virtual Observatory; Galaxies; Stellar Populations; Evolution of Galaxies; Photometry of Galaxies.

1. INTRODUCTION

What is the Virtual Observatory? The Virtual Observatory is a realisation of the e-Science concept in astronomy; it is a *powerful virtual environment* aimed at facilitating astronomical research and increasing scientific output of astronomical data. It is formed by data archives and software tools interoperating using a set of peer-reviewed standards and technologies developed and maintained by the International Virtual Observatory Alliance (IVOA).

What does this really mean? Being naive, the increase of the scientific output of the data means that each Gigabyte of data coming from a given instrument will produce larger number of scientific results, i.e. papers or conference presentations, exactly like uploading a research paper to the preprint server increases significantly its scientific impact.

Figure 1. Similarities between the concepts of WWW (left) and VO (right).

2. SIMILARITIES BETWEEN VO AND WWW

Virtual Observatory is sometimes referred as a World Wide Web for astronomers. Indeed, there are numerous remarkable similarities between the concepts of WWW and VO (Fig 1):

- *IVOA* plays a similar role for the VO as *W3C* does for WWW: these are administrative organisms responsible for the definition of interoperability standards. As examples, we can consider specifications of HTML/XHTML developed by W3C and VOTable developed by IVOA

- *Resources* are the inalienable parts of both concepts. In case of WWW these comprise: (1) web-sites, (2) portals and directories, (3) web-services. In the VO we have: (1) data archives, (2) catalogue access services (e.g. SDSS CASJobs: http://cas.sdss.org/), (3) astronomy-oriented web-services

- *Tools* represent another cornerstone of both, VO and WWW: (1) in WWW we deal with web-browsers (e.g. FIREFOX, INTERNET EXPLORER, SAFARI) while in the VO we have data browser and discovery tools, such as ASTROGRID VO DESKTOP, CDS ALADIN, NVO DATASCOPE; (2) advanced users often deal with command-line tools to access the resources such as CURL or WGET for WWW, and, similarly, VO clients based on access libraries such as ASTRO-RUNTIME; (3) finally, there are specialised clients using WWW/VO protocols as infrastructure and/or data transport, for instance, PICASSA or GOOGLE EARTH with their "analogues" in the VO world such as VISIVO

3. VO SCIENCE AND TECHNOLOGY NOW

In this section I would like to briefly mention the existing accomplishments of the Virtual Observatory.

On the side of IVOA we have a comprehensive set of standards including: data formats (VOTable), VO resource description (Resource Metadata), data model for 1D spectra (Spectrum Data Model) and much more complex and general Characterisation Data Model, Astronomical Data Query Language, protocols to access images and spectra, application messaging protocol allowing different VO tools to talk to each other, authorisation and authentication mechanisms, and others. Many more standards are still at different phases of development. Now it became possible to handle even very complex astronomical datasets in the Virtual Observatory, such as 3D spectroscopy (Chilingarian et al., 2006, 2008a) and results of N-body simulations.

In the meantime, application developers have created an impressive set of VO-enabled tools from those of general interest to very specialised applications. Many of them were presented in the review by M. Allen (this conference).

Data and service providers have contributed to the Virtual Observatory by providing access to numerous data collections and archives at wavelength domains from gamma-ray to radio. First services to access theoretical models (e.g. theoretical spectra of stellar atmospheres in Spanish-VO or PEGASE.2 / PEGASE.HR synthetic stellar populations (Fioc & Rocca-Volmerange, 1997; Le Borgne et al., 2004) in VO-France, access to the results of cosmological simulations in Italian VO) started to appear recently. We should also mention first prototypes of data analysis services and value-added services associated with data access services, such as modelling of the spectrophotometric properties of merging galaxies in the GalMer database (Di Matteo et al., 2008).

The Virtual Observatory has been used for astronomical research for almost 5 years. The first VO-science result was the discovery of optically faint obscured quasars by Padovani et al. (2004). This was an example of a multi-wavelength study carried out entirely inside the VO infrastructure. Three years later, the VO studies of obscured AGN were continued (Richards et al., 2007).

A number of refereed papers were published by the Spanish VO project members, presenting discoveries of unique objects done with the VO tools (Caballero & Solano, 2007, 2008; Caballero & Dinis, 2008).

A paper by Bayo et al. (2008) presenting VO SED Analyzer is of particular interest, as the first refereed paper presenting a "virtual instrument", i.e. a service in the VO aimed at data analysis, as well as its application to a particular research project.

Many other studies made use of the VO tools and infrastructure combining them with proprietary data access and analysis. For example, in Chilingarian & Mamon (2008), authors used the VO data discovery and access mechanisms to collect all existing data on a newly discovered object. This example demonstrates how difficult may be to define the concept of a VO study or VO-enabled study.

Nearly all research projects mentioned above used Virtual Observatory to do data discovery, data access, and data mining. Therefore, the principal question I would like to address is: Is it already possible to go beyond data mining? The answer is: Yes, it is.

4. VO SCIENCE BEYOND DATA MINING

In this section I describe two VO-enabled research projects making heavy use of VO technologies beyond data mining. The VO is used in connection with dedicated observations and numerical simulations demonstrating the proof-of-concept for such complex studies.

4.1. Compact Elliptical and Tidally Stripped Galaxies

This study was inspired by the serendipitous discovery of a very rare compact elliptical (cE) galaxy in the central part of the nearby galaxy cluster Abell 496 (Chilingarian et al., 2007a) which became the 6th known galaxy of this class in the Universe.

Compact elliptical galaxies have similar luminosities ($-18 < M_B < -15$ mag) and stellar masses to dwarf ellipticals, but 10 smaller effective radii ($r_e \sim 100 - 200$ pc) and, therefore, 100 times higher surface brightness and 1000 times larger stellar density per unit of volume. The prototype of the cE type is Messier 32, a satellite of the Andromeda galaxy. All known cEs reside in the vicinities of larger stellar systems and/or in the innermost regions of galaxy clusters.

Compact ellipticals are thought to be tidally stripped intermediate-luminosity galaxies (Nieto & Prugniel,

1987; Bekki et al., 2001; Graham, 2002), additional arguments for this scenario have been provided by Chilingarian et al. (2007a) from stellar populations. However, low statistics did not allow us to uniquely argue for this scenario of cE formation.

Given small spatial sizes of cEs they become spatially-unresolved in ground-based observations for distances beyond ∼50 Mpc. Their broadband optical colours well resemble K-type Galactic stars giving them little chances to be included into the samples of large spectroscopic surveys such as SDSS.

The key advantage here is provided by the Hubble Space Telescope, which can efficiently resolve these little galaxies up-to a distance of 200 Mpc, allowing us to study their structural properties. We realised this in the course of our study of the Abell 496 cluster of galaxies (Chilingarian et al., 2008b), and decided to search for cE galaxies using the power of the Virtual Observatory to study the role of tidal stripping in the galaxy evolution. All details about this project will be soon provided in Chilingarian et al. (in prep.), here we give a brief overview.

We have constructed a workflow including the following steps:

1. querying Vizier Catalogue Service to retrieve a list of galaxy clusters having $z < 0.055$;

2. querying NED to retrieve their precise coordinates and values of Galactic extinction;

3. querying fully-reduced direct images obtained with HST WFPC2 and ACS from the Hubble Legacy Archive (HLA) using Simple Image Access Protocol (SIAP);

4. running SExtractor (Bertin & Arnouts, 1996) as a remote tool on these images (no image download is required);

5. selecting extended objects having low ellipticity, effective radii below 0.7 kpc and B-band mean effective surface brightness higher than 20 mag/arcsec^2;

6. querying NED to check if there are published redshifts for the selected objects and obtaining additional photometric data

Having applied the workflow to the entire WFPC2 data collection in the HLA we ended up with the archival images of 63 clusters with several dozens candidate cE and tidally stripped galaxies in 30 of them. We found a large number of objects in the scarcely populated region of the R_e vs $\langle\mu\rangle_e$ and M vs $\langle\mu\rangle_e$ diagrams reflecting structural properties of galaxies.

In Fig 2 we present the structural properties of newly discovered cE and tidally stripped galaxy candidates in comparison with dwarf (Binggeli & Jerjen,
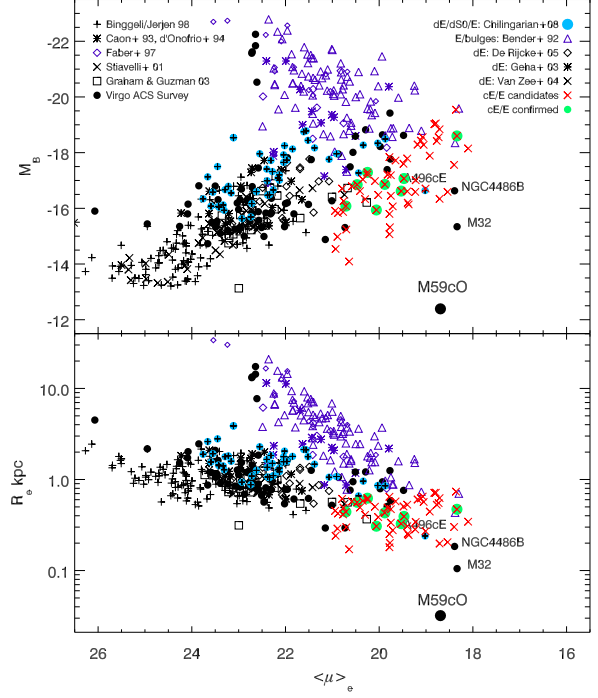

Figure 2. Structural properties of early-type galaxies. See sources of data in the text. New cE and tidally stripped galaxy candidates discovered using the VO are shown by red crosses on-top of green circles for objects with spectroscopic confirmation.

1998; Stiavelli et al., 2001; Graham & Guzmán, 2003; Geha et al., 2003; van Zee et al., 2004; De Rijcke et al., 2005; Ferrarese et al., 2006; Chilingarian et al., 2008b), intermediate-luminosity (Bender et al., 1992), giant (Bender et al., 1992; Caon et al., 1993; D'Onofrio et al., 1994; Faber et al., 1997) early-type galaxies, three nearby compact ellipticals and transitional cE/UCD object (Chilingarian & Mamon, 2008).

Our workflow may have confused cE galaxies with (1) foreground or cluster compact star-forming galaxies; (2) background giant early-type galaxies hosting bright active nuclei (AGN); (3) background post-starburst galaxies. The star-forming galaxies can be discriminated automatically by their blue colours if multi-band data are available or manually by clumpy morphology. The two remaining cases may arise when the distance to the background object is 2–3 times the distance to the cluster, i.e. <400–500 Mpc ($z < 0.12$) in our study. Then, AGNs can be ruled out by checking X-ray point source catalogues, and the probability of having a post-starburst galaxy at this redshift is very low (Goto, 2007).

The next stage of the project was to obtain high-quality optical spectroscopic data on some of the candidates.

We have observed three galaxy clusters, Abell 160 (Fig 3), Abell 189, and Abell 397 hosting 8 candidate galaxies ($-17.0 < M_I < -19.5$ mag)

with the multi-slit unit of the SCORPIO spectrograph (Afanasiev & Moiseev, 2005) at the Russian 6-m "Bol'shoi Telescop Azimutal'nyy" (BTA) in August 2008. We have analysed the spectra by fitting them against high-resolution PEGASE.HR stellar population models using the novel NBURSTS full spectral fitting technique (Chilingarian et al., 2007b,c), and obtained precise radial velocities, internal velocity dispersions, luminosity-weighted stellar ages and metallicities. All 8 candidate objects were confirmed to be cluster members having stellar populations older than 8 Gyr with metal abundances typically between $Z_\odot/2.5$ and the solar value ($Z_\odot/5$ for one object) and internal velocity dispersions between 50 and 100 km s^{-1}.

We have performed numerical simulations of tidal stripping of intermediate-luminosity early-type disc galaxies by the potential of the galaxy cluster including the central cD galaxy using the GADGET-2 code (Springel, 2005). The simulations suggest that the progenitor galaxies may entirely lose their discy components due to tidal stripping, while keeping the bulges although with significant stellar mass loss as well. The remnants of the tidal stripping for some initial conditions and orbital configurations well resemble the observed properties of cEs, although in most cases they are still remain quite extended. This explains why cE galaxies are not very common.

We have faced a number of issues while undertaking this project, most of them are infrastructural.

- There is no real VO access to NED. We had to develop and use "home-made" scripts to execute queries.

- SIAP interface in the HLA is not publicly announced, although it is used internally in the project. The service URL has been provided privately to us by the HLA developers, although it was possible to get it by reverse engineering of the JavaScript code.

- We had to setup a customized SExtractor service and spend a lot of time to fine-tune it by using some undocumented features.

- It took 3 semesters to convince the TAC to approve our telescope proposal.

- We were the first to use the SCORPIO multi-slit mode with the high-resolution grism, therefore it was necessary to design and develop the data reduction pipeline.

The main result of our study is that the class of cE galaxies is converted from "unique" into "common under certain environmental conditions". We provide evidences for the importance of tidal stripping of stellar discs as a way to create peculiar early-type galaxy population in the cluster centres. Now we can explain the existence of very strange objects such as VCC 1199 having supersolar metallicity for a very low luminosity of $M_B \approx -15$ mag.

This was the first study, where the primary step was done in the VO, then the discovered objects were followed-up with a large telescope and successfully reproduced by numerical simulations.

4.2. Optical and Near-Infrared Galaxy Colours

While preparing my presentation for this meeting, I decided to make something special. The challenge was to get valuable results related to studies of galaxies *in one week* using the VO starting the project from scratch. My main collaborator in this project was I. Zolotukhin, located geographically in a different place, so we had to work remotely and interact only online.

We decided to study optical and near-infrared colours of nearby galaxies and try to connect them to their stellar population properties. NIR magnitudes are less sensitive to the stellar population age compared to the optical colours, therefore they can be used as better stellar mass tracers (although not perfect). In addition, the effects of extinction inside the galaxies being studied are less important in the NIR spectral bands. Spectroscopic information on stellar ages and metallicities should become additional important bricks of information. The catalogue will be presented in Chilingarian, Zolotukhin & Melchior (in prep.)

We have used the following resources:

- SDSS DR7 (Abazajian et al., 2008) photometric catalogues as a source of optical magnitudes

- SDSS DR7 spectra to get stellar population properties by the full spectral fitting

- UKIDSS (Lawrence et al., 2007) DR4 Large Area Survey (LAS) catalogue as a source of NIR magnitudes

The techniques we have exploited:

- position-based cross-match (possible to do in the VO)

- stellar population modelling using PEGASE.2/PEGASE.HR (possible to do in the VO)

- NBURSTS full spectral fitting technique (yet as a stand-alone non-VO service)

From the zoo of VO tools we selected TOPCAT/STILTS to join and merge large tables, scripts-based access to SDSS, and ASTROGRID VO DESKTOP to access UKIDSS catalogues and perform the cross-match.

We have used SDSS CASJobs to select all galaxies from the spectroscopic sample having redshifts $0.03 < z < 0.3$ in the SDSS stripes 9 to 16 which have been partially
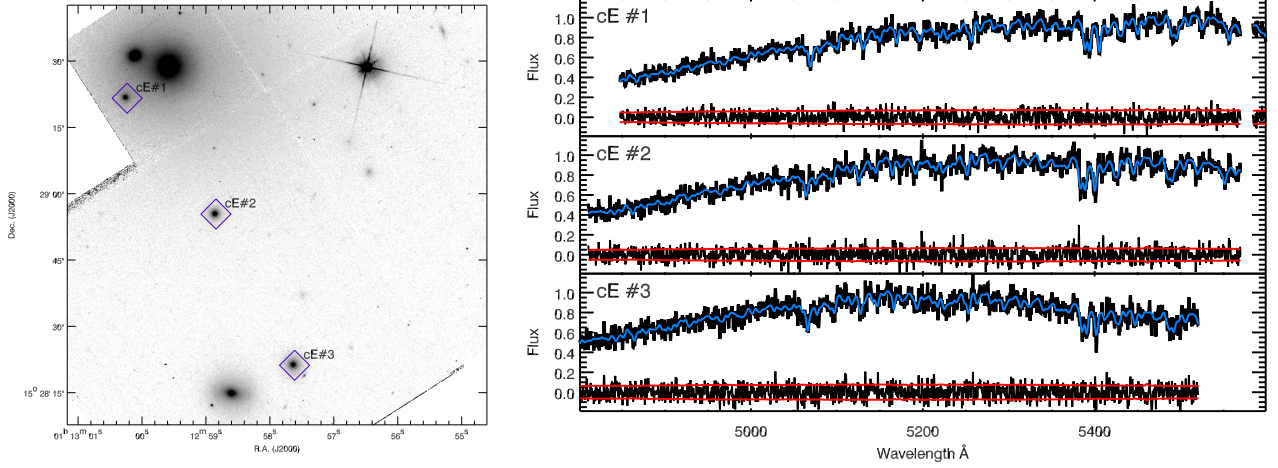
Figure 3. HST WFPC2 image of the Abell 160 cluster with three confirmed cE galaxies outlined (left). Spectra of these three objects obtained with the SCORPIO universal spectrograph (right) with their best-fitting templates as provided by the NBURSTS full spectral fitting technique.

covered by the UKIDSS. This query has returned approximately 170 thousand objects.

Then, we have cross-matched this list against the UKIDSS DR4 LAS catalogue with a search radius of 5 arcsec. This step can be done either using WFCAM Archive or through the ASTROGRID VO DESKTOP application using the multi-cone search interface. Notice, that the access to UKIDSS DR4 was restricted, therefore to query it in an automatic way it was necessary to use the authorisation/authentication mechanisms provided by the VO.

Then we have computed and applied K-corrections by fitting optical-NIR spectral energy distributions (SEDs) against PEGASE.2 stellar population models to get rest-frame magnitudes.

At the final step, we have processed all selected SDSS DR7 spectra using the NBURSTS full spectral fitting technique in order to estimate velocity dispersions, ages, and metallicities of all galaxies in 3-arcsec wide apertures.

The non-trivial problem is the homogenisation of the photometric data. Firstly, we tried to use the Petrosian magnitudes provided in both catalogues, but we quickly realised that due to very different sensitivity of the two surveys the Petrosian radii used to measure the magnitudes may be very different and the difference is correlated with the galaxy colours. Finally, we decided to deal with fluxes in the 3 arcsec wide apertures, which are provided directly by SDSS and easy to compute for UKIDSS using the three provided aperture magnitudes. These magnitudes may not reflect the real total colours of galaxies, since our fixed aperture corresponds to different spatial sizes at different redshifts, but, for explaining the colour properties using additional spectroscopic information obtained by the SDSS in the same apertures, this approach is preferable.

Another important problem is the K-correction, or dependence of colours on the redshift due to the fact that the filter transmission curves effectively contain different regions of galaxies' SEDs at different redshifts. There are several existing prescriptions for the computation of K-corrections (Mannucci et al., 2001; Blanton & Roweis, 2007), however, they provide controversial information for the NIR spectral bands. Therefore, we have decided to deduce K-corrections from the multi-wavelength SED fitting of the data against the PEGASE.2 SSP models redshifted according to the spectroscopic information and varying the effects of internal dust extinction. The behaviour of K-corrections in the optical bandpasses obtained in this fashion well resembles the results of Blanton & Roweis (2007). At the same time, our NIR K-corrections turned to be very different, however, well corresponding to those presented in Mannucci et al. (2001).

Since we had optical spectra available from SDSS for all the galaxies in our sample, we computed the actual values of flux differences by integrating the spectra in the rest-frame and redshifted filter bandpasses unless they moved out of the spectral coverage. Given the wavelength range of SDSS spectra we were able to compute the "true" K-corrections for the g band for any redshift, for the r band for objects having $z < 0.25$, and for the i band till $z < 0.08$. These "true" values perfectly agree with the values derived from our SED fitting with a typical errors not exceeding 0.05 mag. Therefore, we conclude that our prescriptions for the computation of K-corrections have reasonable quality for the studies of optical/NIR galaxy colours. The full discussion related to the computation and applications of K-corrections for nearby galaxies will be provided in Chilingarian, Melchior & Zolotukhin (in prep.)
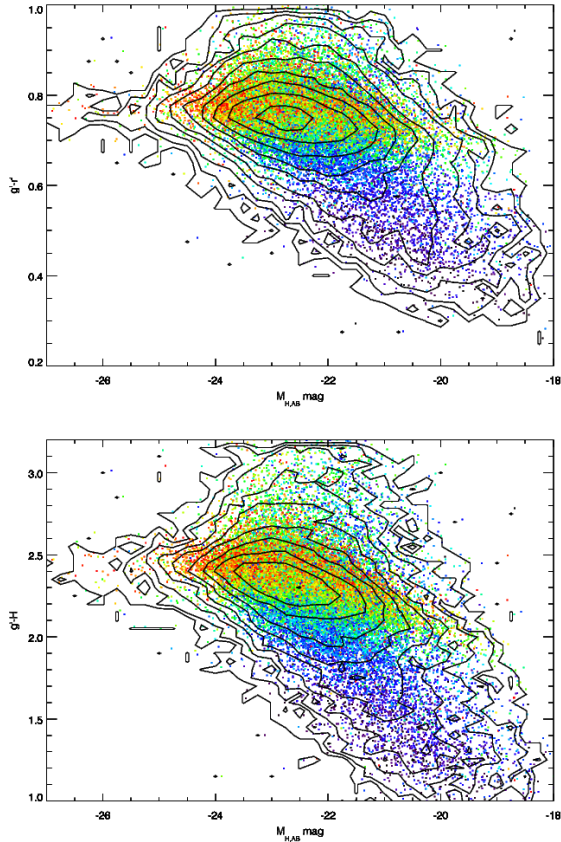
We have also faced a number of technical issues:

Figure 4. Colour-magnitude diagrams for nearby galaxies: optical and NIR colours. All magnitudes are extinction- and K-corrected. The top and bottom panels present $g - r$ vs M_H and $g - H$ vs M_H respectively. The SSP-equivalent ages are colour coded, values from violet to red correspond to 1 to 15 Gyr.

- SDSS DR7 is not accessible via VO protocols, therefore we used its own CASJobs portal.

- There were numerous problems accessing UKIDSS DR4 through the VO due to bugs in the implementation of services and access interfaces. However, all these questions have been solved very efficiently by the UKIDSS and Astrogrid teams.

- Need to download, upload, merge, and convert lengthy tables.

- Still there is no way to perform the cross-match against user-uploaded table using the ADQL queries: these mechanisms are still to be implemented

In Fig 4 we present the colour–magnitude plots for the galaxies from our sample. We use the rest-frame H magnitude which is much less sensitive to the effects of stellar age than optical bands. Spectroscopic ages obtained from the full spectral fitting are colour-coded. It is immediately evident that the red sequence (Strateva et al., 2001)

is populated by old galaxies, while in the blue cloud there is a significant age gradient.

There is a 3-magnitude long high-luminosity tail of the red sequence clearly seen on the plots, providing an immediate evidence that such galaxies cannot be formed by equal-mass mergers of objects from the blue cloud.

Another feature seen in the $g - H$ vs M_H plot is a population of young and intermediate-age objects overlapping the red sequence and sometimes being as much as 0.7 mag redder in the $g - H$ colour. These are probably dusty galaxies with active star formation, so the superposition of young and all populations, plus dust attenuation creates such an appearance.

This project is still very far from being finished. We foresee to add GALEX ultraviolet data and fit SDSS spectra together with photometric data points with more realistic galaxy models than simple SSPs, for example, to include two star formation episodes with different dust attenuation for them. We also plan to study the distribution of emission line strengths since we are able to precisely model the stellar population, making feasible studies of even very faint emission lines.

5. SUMMARY

The Virtual Observatory is already at the production level. Scientists not associated directly to VO projects are trying to feel the way. The scientific results already obtained are impressive and very important as a proof-of-concept. The advantages of the VO approach are clear: one can transparently access and process enormous volumes of data from different sources. But, of course, the VO should not be considered as replacement for scientists – it is just a tool to help them.

In my opinion, the major problem for a scientist in the VO now is very little, but numerous and, therefore, annoying infrastructural faults: all the individual bricks exist, but them together still requires a lot of efforts.

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